# Stratospheric ozone trends in the SAGE II – OSIRIS – SAGE III/ISS composite dataset*

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# Stratospheric ozone

- Polar ozone continues to experience significant springtime depletion
- The near-global ozone column (excluding the polar regions) remained largely constant since ozone decline stopped near the turn of the century
  - Some positive trends are now emerging in the SH [Weber et al., 2022]
  - Total (or even stratospheric) column ozone doesn’t tell the whole story
    - Tropospheric trends, circulation changes complicate the picture
- Stratospheric ozone trends are altitude-dependent
  - The decline of ozone-depleting substances (ODSs) is not necessarily the primary driver
  - Increasing greenhouse gas (GHG) concentrations are expected to:
    - Cool the stratosphere → slow reaction rates → reduce depletion in the upper stratosphere
    - Accelerate the Brewer-Dobson circulation (BDC) → enhance upwelling, change circulation patterns in the lower stratosphere

# Upper stratospheric recovery

- Statistically significant at 1-3 %/decade
- Greatest confidence in NH
  - Variable across datasets
- Contribution of ODS decline and GHG increase is about equal [WMO, 2018]
- In agreement with chemistry climate model (CCM) predictions
- Different story in the lower stratosphere
  - CCMs predict decline in tropics, increase at mid-latitudes (enhanced upwelling)
  - Most satellite datasets don't exactly agree

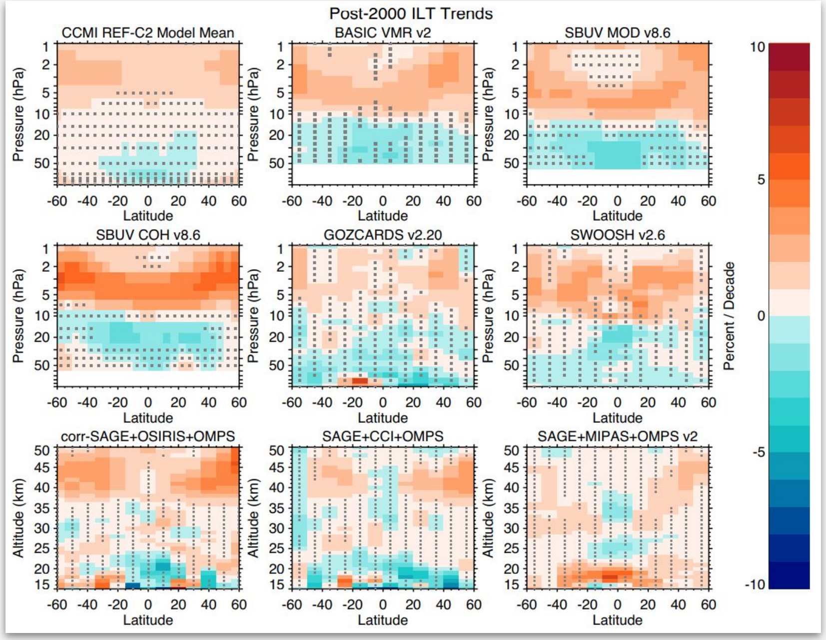



Figure 5.2 from the LOTUS report [Petropavlovskikh et al., 2019]: ozone trends for 2000-2016.

# Lower stratospheric decline

- Controlled by dynamics, not ODS concentrations
- Tropics: most datasets indicate negative trends
- Northern mid-latitudes: also negative, more than offsetting recovery at higher altitudes
    - Non-linear quasi-biennial oscillation (QBO) interactions [Ball et al., 2018, 2019]
    - Enhanced isentropic mixing [Wargan et al., 2018]
    - Expansion of upwelling [Orbe et al., 2020]
- Natural variability impacts trend estimates
    - Large anomalies might change trend results from year to year [Chipperfield et al., 2018]
    - Strong seasonality is present [Szeląg et al. 2020]

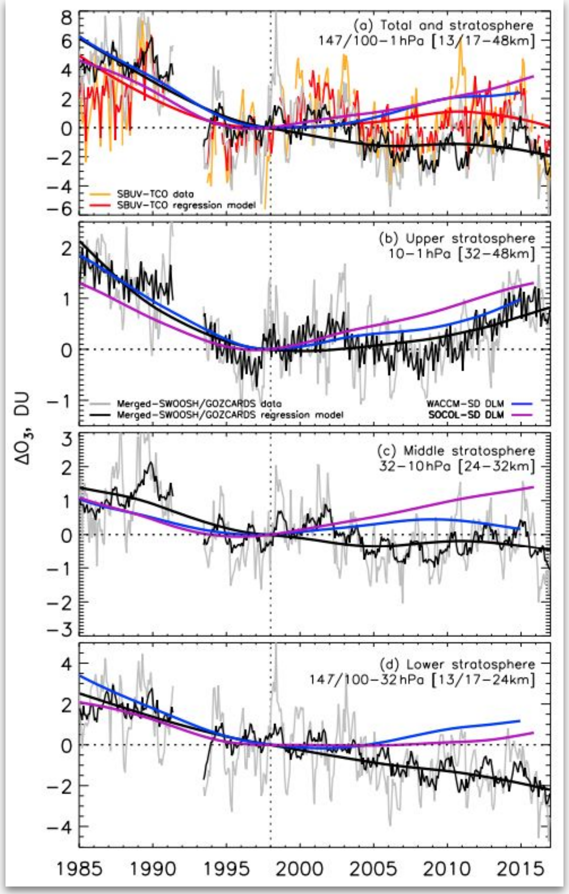



Figure 3 of Ball et al. [2018]: 1985-2016 ozone trends from the BASIC composite.

# Challenges, motivations

- Magnitude and significance (even the sign at low altitudes) of stratospheric ozone trends is still in question
    - Long-term datasets are required: combine a variety of measurement methods, viewing geometries, and sampling patterns. Combine how?
    - Time periods, fit methods have a major impact on trend results
- To address this:
    - We combine sampling-corrected datasets from similar instruments
    - Carefully assess trend significance using external data (MLS measurements)
    - Compare results from two fitting methods
- SAGE II – OSIRIS – SAGE III/ISS (SOS) composite
    - First inclusion of SAGE III/ISS in a published dataset

# Methodology

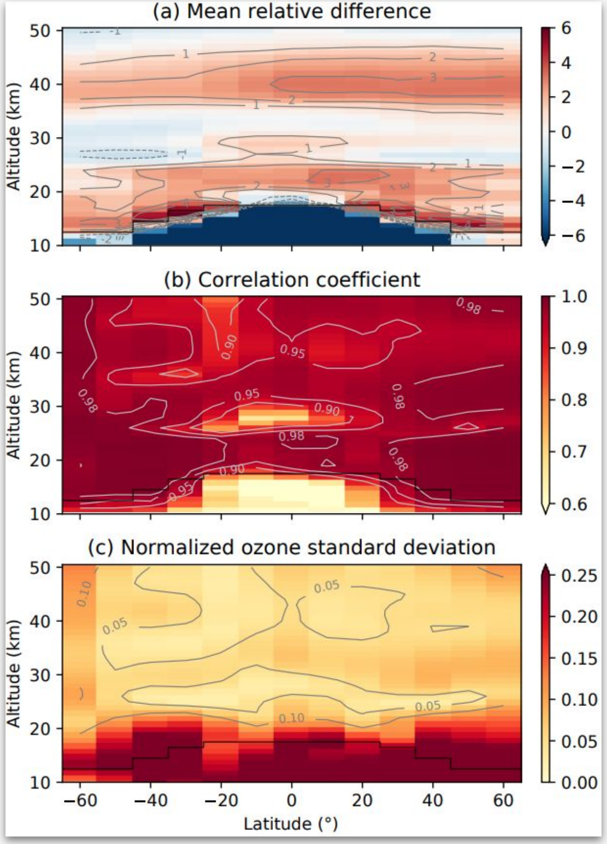
# The SOS composite

| Dataset | Coverage |
|---|---|
| SAGE II v7.0 | 1984 – 2005 |
| OSIRIS v7.2 | 2001 – 2021 |
| SAGE III/ISS v5.2 | 2017 – 2021 |

- Monthly zonal mean (MZM) data
- Tropopause filter prior to merging
  - Lapse rate tropopause height for each ozone profile calculated from MERRA-2 temperatures
  - Use second tropopause when present
  - Only data above the tropopause height is considered
- Merge MZM relative anomalies [Bourassa et al., 2014, 2018]
  - Each dataset is deseasonalized independently
  - SAGE datasets are adjusted such that differences w.r.t OSIRIS in the overlap periods are zero
- Common grid 10° latitude by 1 km altitude
  - Grid centers of 13-50 km, 60° S - 60° N
  - Lower boundary adjusted to mean + 1σ tropopause height

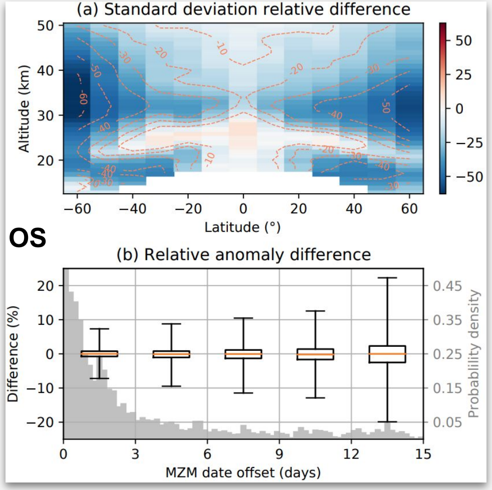
# The SOS composite – OSIRIS v7.2

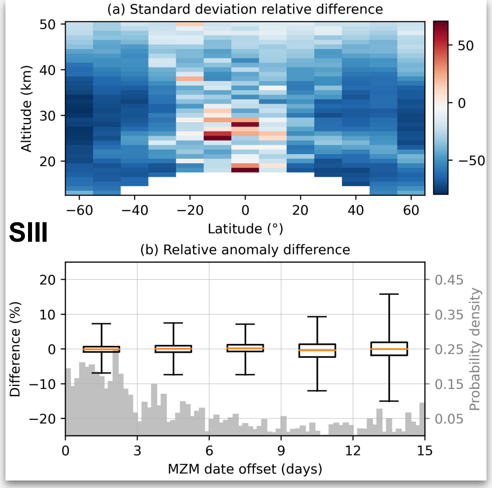
- New data version
  - An update of v5.10 ozone
- New fit method (Levenberg-Marquardt alg.)
- Point spread function correction
  - Reduces temperature-dependent effects
- Updated inputs; optimized retrieval
- Compared to v5.10:
  - Minor changes, excellent correlation
  - SZA-dependent bias removed
  - Effect of seasonal temperature oscillations reduced
- Only using descending node measurements



# The SOS composite – sampling correction

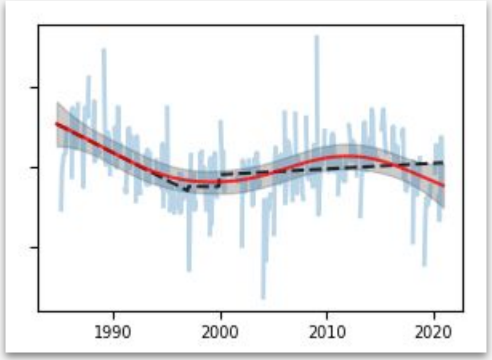
- Sampling patterns mean MZM values are biased
- Use MERRA-2 ozone to transfer each profile to the center of the month/latitude bin
  - Performed for OSIRIS and SAGE III/ISS
  - Ratio of coincident MERRA-2 profile with MERRA-2 profile at middle of month/latitude bin (at the same longitude)
  - Preserves longitudinal and random variability
- Greatly reduces variability along latitude and time axes
  - More noise in tropics, where variability is low
  - Largest changes for bins that are not sampled well
  - No overall sampling bias
  - Reduces effects of changing sampling patterns over time
- SAGE II: sampling-corrected dataset of Damadeo et al. [2018]



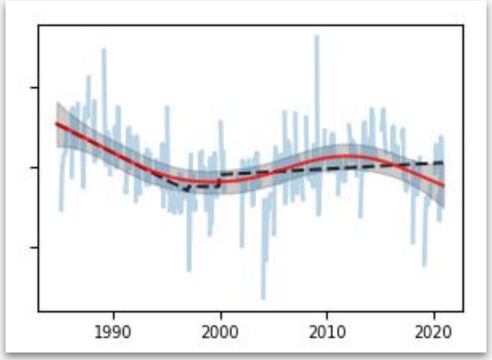
# Trend analysis

- Multiple linear regression (MLR)
  - Two linear components (connected or independent)
    - Endpoint anomalies affect each component
    - Inflection point/period needs to be specified
  - Uncertainties: variance of fit parameters (use 2σ)
  - LOTUS regression model [Petropavlovskikh et al., 2019]
- Dynamic linear model (DLM)
  - Smooth, non-linear trend
    - Endpoint anomalies affect the first/last few years only
    - Inflection point (if exists) is fitted
  - Full uncertainty characterization (assuming model is correct)
  - dlmmc model [Alsing, 2019], also in Ball et al. [2018, 2019]
  - Used for most of the results here



# Trend analysis (cont’d)

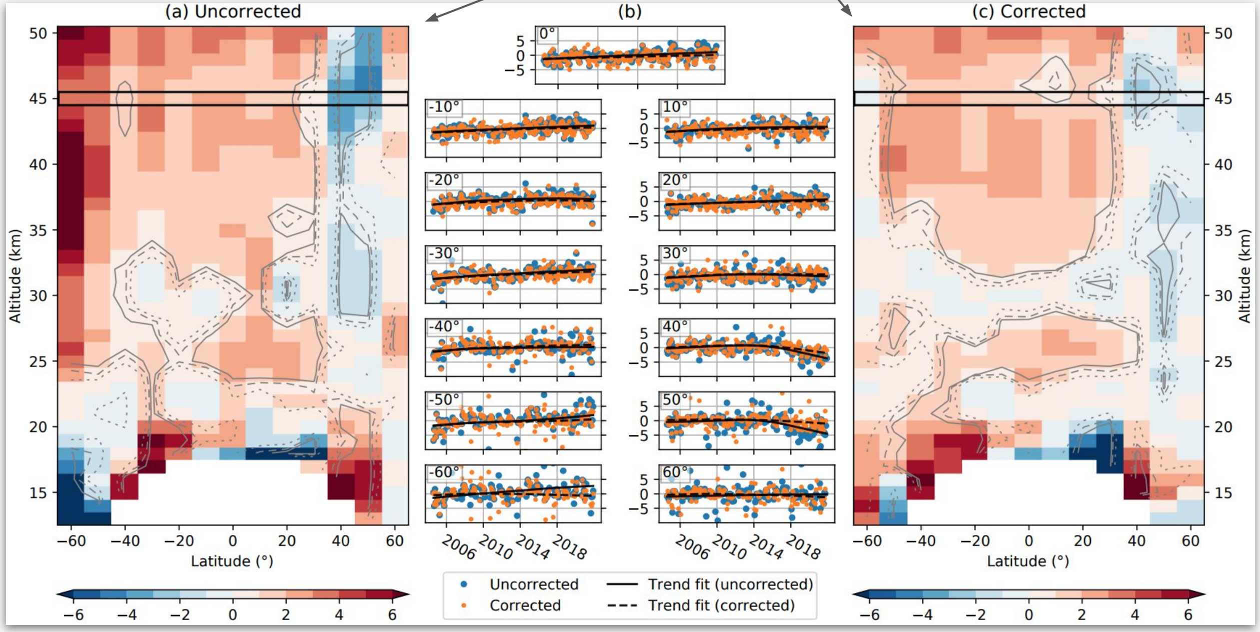
- Regressors:
  - El Niño index, QBO (2 PCs, with seasonal components), F10.7 cm solar index, latitude-dependent aerosol optical depth (GloSSAC v2.1)
  - MLR only: independent linear trends (1984-1996, 2000-2021)
- DLM details:
  - Only the prior on the degree of trend non-linearity is specified
  - Regressor coefficients constant → equivalent to MLR
  - Parameter estimates: 10 000 MCMC samples
  - Ozone change: difference of yearly means for 2000 and 2021 (forms a distribution)
- Only the post-2000 trends are considered
  - Fit is performed on entire dataset (1984-2021)
  - MLR trends are scaled to the 2000-2021 period



# Uncertainties: SOS vs MLS v4.2

- Additional constraint on trend significance
  - How does significance change if potential drifts between the datasets are taken into account?
  - Plenty of assumptions
- Time series differ, especially in lower stratosphere
- Fit the SOS minus MLS relative anomalies using DLM
  - Subtract mean trend from each SOS trend sample
- Byproduct: validates sampling correction

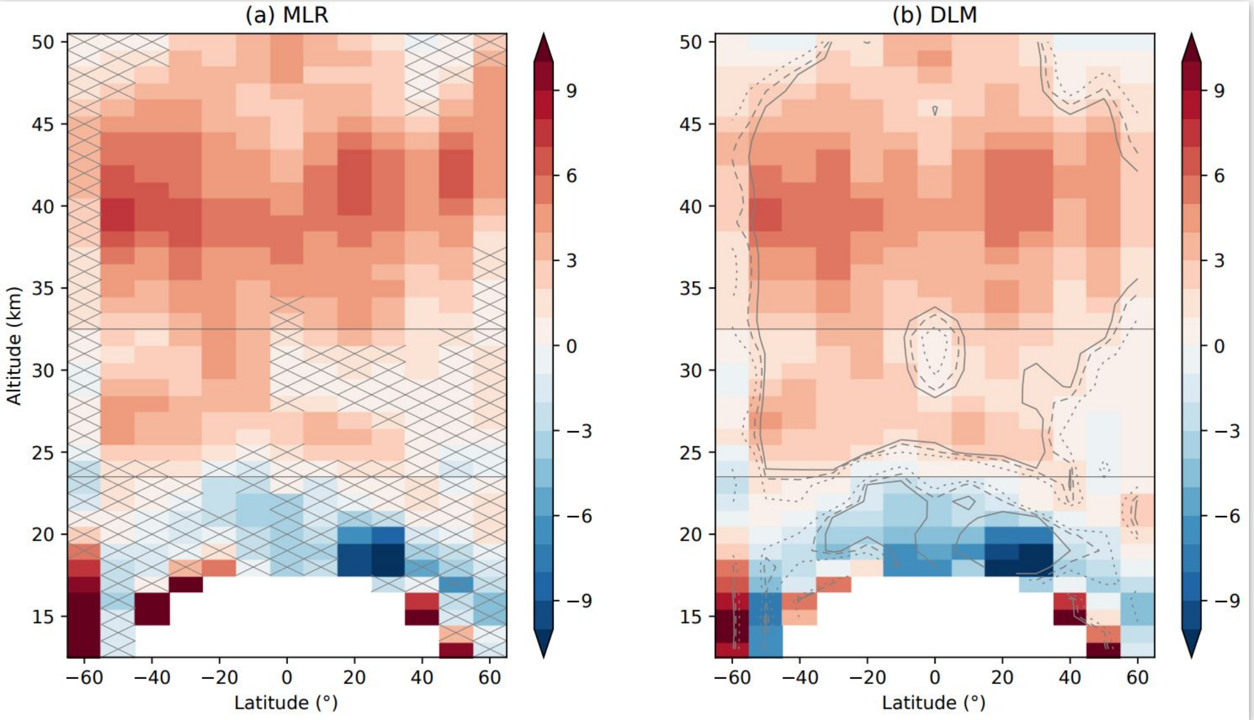
Percent change in differences from from 2005 to 2021



# SOS ozone trends

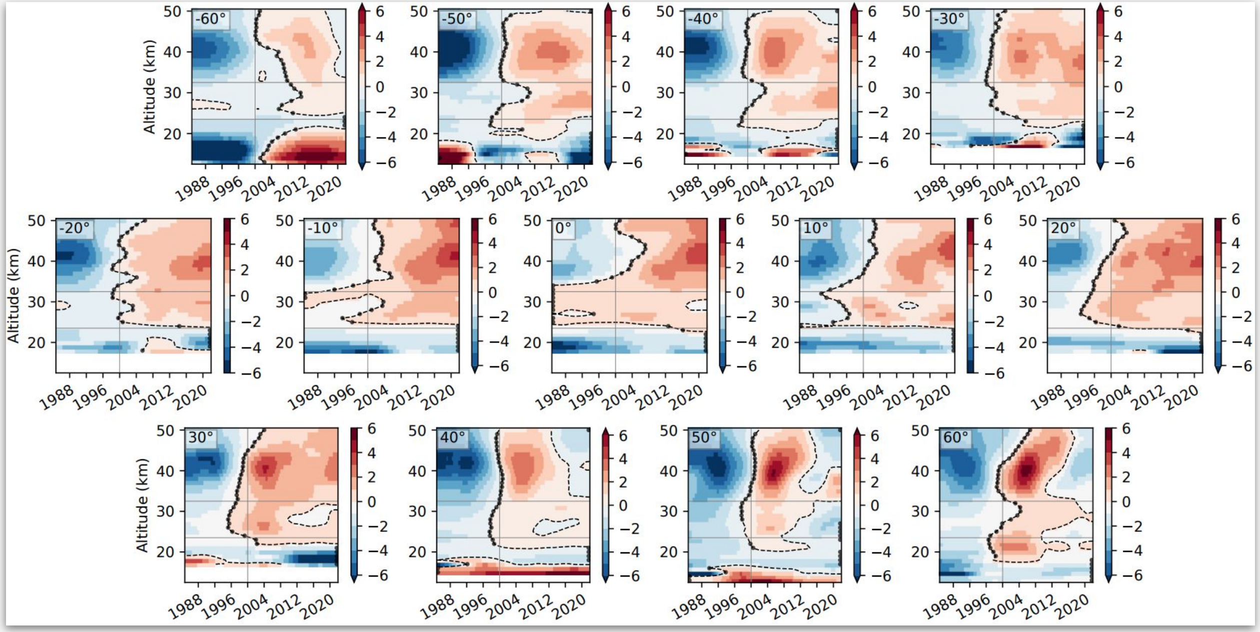
# 2000-2021 ozone trends

- MLR and DLM results are generally similar
- Upper stratosphere:
  - Robust ozone recovery (2-6 % since 2000)
  - As in WMO [2018]
- Middle stratosphere:
  - Smaller increases
  - Hemispheric asymmetry
- Lower stratosphere:
  - Consistent negative trends, especially in the tropics
  - Similar to Ball et al. [2018, 2019]; to a lesser extent Szeląg et al. [2020]



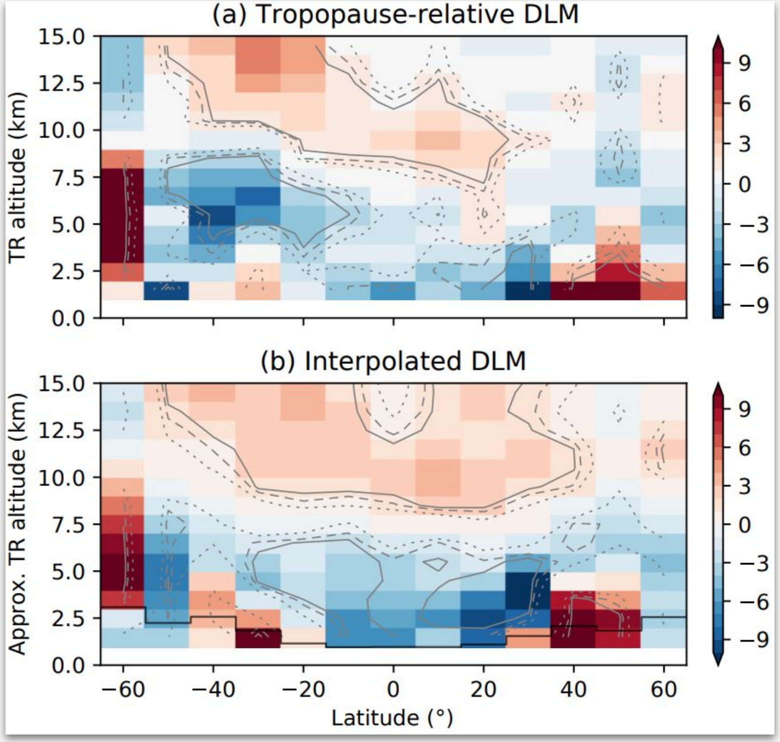
# 2000-2021 ozone trends – DLM slopes

- Ozone rate of change, scaled to percent per decade
- Turnaround dates center around 2000, but are variable
- Linear change is not always a good estimate
  - See 40-60° N
- Continuous decline in tropical lower stratosphere
  - Minimum values (black dots) are in 2021
- Mid-latitude ozone change is highly variable
  - 2000 is not a meaningful baseline



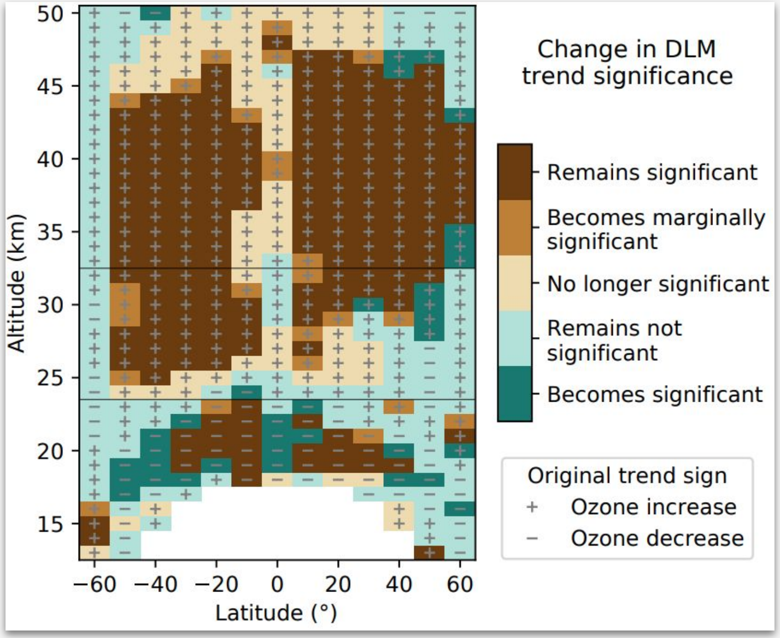
# Tropopause-relative trends

- Tropical ozone decline typically associated with acceleration of the BDC
- Tropospheric warming leads to tropopause height increase
  - Stratospheric circulation is lifted
  - Might explain some of the BDC and ozone trends
- Tropopause-relative dataset
  - Each profile is adjusted to the tropopause height (prior to averaging or merging)
- Trends in the tropics are reduced in magnitude and significance
- Similar to recent ozonesonde trends [Thompson et al., 2021]



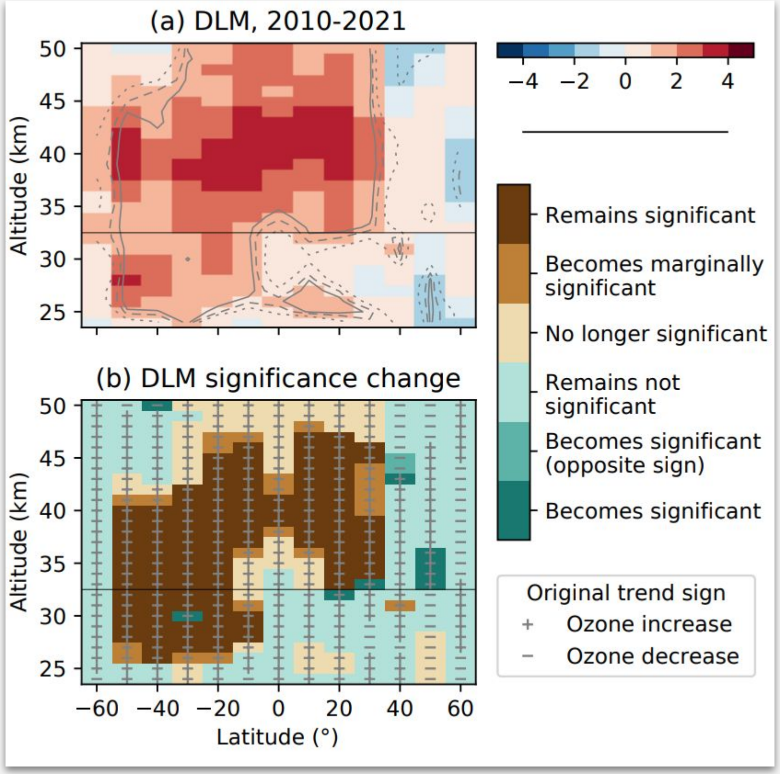
# Trend significance

- Change of trend significance when the DLM distribution is adjusted with the time-dependent SOS-MLS differences
- Trends are robust in most of the upper and middle stratosphere
  - No increase at high altitudes: similar to Ball et al. [2019]
  - More pronounced asymmetry at ~25-30 km
- Negative trends in the lower stratosphere are likely more significant than SOS data indicate
  - Comparisons are less representative due to the tropopause filter



# Recent trends – pause in NH recovery?

- 2010-2021 ozone change from the non-linear DLM trends
- No increase at northern mid-latitudes
  - Or in the entire NH middle stratosphere
  - Mostly independent of SOS-MLS differences
- Impact of the dataset end year:
  - Middle stratosphere: large differences apparent for 2020, 2021 only
  - Upper stratosphere: same pattern for 2017-2021
- Longitudinal variability in the NH [Arosio et al., 2019; Sofieva et al., 2021]
- BDC upper branch: asymmetric changes, long-term variability [Strahan et al., 2020; Prignon et al., 2021]



# Conclusions

- Sampling-corrected SAGE II – OSIRIS – SAGE III/ISS composite for near-global trends
  - Using both MLR and DLM for trend fitting: DLM results capture ozone changes better
- Since 2000, upper stratospheric ozone increased by 2-6 %
  - Significant and robust in both hemispheres
  - Pattern extends down to the middle stratosphere in the SH only
- Ozone recovery appears to have paused in the NH during the last decade
  - Not quite long enough to rule out low frequency BDC variability
- Tropical lower stratospheric ozone shows continuous decline since 1984
  - In part due to rising tropopause heights
- At mid latitudes, negative trends extend to ±50° at 17-20 km
  - SOS data likely underestimate significance
- Next steps: detailed CCM comparisons
  - Work ongoing at USask

# Thanks!

Now at:

3vGeomatics, developing algorithms for radar satellite imagery (InSAR)

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